Chapter 1

Introduction and Overview

1.1 Purpose

Radon is a naturally occurring radioactive gas in ambient air. It can also accumulate in varying amounts in enclosed buildings. Radon is estimated to cause many thousands of lung cancer deaths each year. In fact, the Surgeon General has warned that radon is the second leading cause of lung cancer in the U.S. today. Only smoking causes more lung cancer deaths (1).

Our increased understanding of the risks posed by indoor radon has underscored the need for construction techniques that prevent exposure to radon in residential and non-residential buildings. The Indoor Radon Abatement Act of 1988 states, "The national long-term goal of the United States with respect to radon levels in buildings is that the air within buildings should be as free of radon as the ambient air outside the building." This manual is intended to address this goal in the new construction of schools and other large buildings.

The U.S. Environmental Protection Agency (EPA) has developed construction techniques that are being used to reduce radon levels in new buildings. This manual provides architects, engineers, designers, builders, and school officials with an understanding of operating principles and installation instructions for these radon prevention techniques. Research indicates that many radon prevention features can be installed relatively easily and inexpensively during building construction. Installing these features during construction increases their effectiveness and involves less labor, disruption, and cost than when these same features are installed after the building is completed and occupied. Thus, the primary purpose of this manual is to provide information and guidelines about radon prevention techniques so that they can be cost-effectively incorporated into a building during the design and construction stages.

1.2 Scope and Content

This manual is divided into two parts:

Chapter 1—Introduction and Overview: Chapter 1 of this manual is a general introduction for those who need background information on the indoor radon problem and the techniques currently being studied and applied for radon prevention. The level of detail is aimed at developing the reader's understanding of underlying principles and might best be used by school officials or by architects and engineers who need a basic introduction to radon and radon reduction techniques. Those who are already familiar with the problems of constructing radon-resistant buildings should go on to Chapter 2. Chapter 1 contains the following sections:

1.3 Radon and Its Sources—an introduction to the problem of indoor radon.

1.4 Radon Prevention Techniques—an overview of current construction methods for radon prevention.

1.5 Why Radon Prevention Should Be Considered in Building Design.

Chapter 2—Technical Construction Information: Chapter 2 of this manual provides comprehensive information, instructions, and guidelines about the topics and construction techniques discussed in Chapter 1. The sections in Chapter 2 contain much more technical detail than Chapter 1, and may be best used by the architects, engineers, and builders responsible for the specific construction details. From the information presented in this manual, readers should be able to select radon prevention techniques that are appropriate to their particular situation.

Chapter 2 also briefly covers sources of information on measuring radon in schools and other large buildings. Appendix A contains a case study of a step-by-step installation of radon prevention techniques in a recently constructed large building. Radon levels and associated costs of the radon prevention features are included. References are in Appendix B, and Appendix C lists the EPA Regional Offices.

The recommendations in this manual are based on the best available information gathered from numerous research projects in existing and new construction, and in current field practice. Most new schools and other large buildings use slab-on-grade construction; therefore, this manual focuses on radon prevention techniques that can be applied to slab-on-grade buildings. But because radon can enter a building regardless of its foundation type, it also presents techniques applicable to buildings with basement and crawl space foundations.

As research continues and experience in the application of radon-resistant construction techniques grows, a variety of techniques might also prove effective in reaching radon reduction goals. These goals are to keep radon levels in new construction well below the currently recommended EPA action level of 4 pCi/L and as close to the long-term national goal of ambient radon levels (0.4 pCi/L) as possible. Many of these radon prevention techniques will eventually prove to be transferable to the architect's and engineer's common practices and, it is hoped, will be adopted in national building codes by the model building code organizations. EPA is currently working with the American Society of Testing and Materials (ASTM) to develop a standard for radon prevention in the construction of large buildings.

1.3 Radon and its Sources

The following subsections answer three basic questions that many people have about radon:

1) Why is radon a problem?

2) How does radon enter a building?

3) How should one evaluate a construction site?

1.3.1 Why is Radon a Problem?

Radon is a colorless, odorless, radioactive gas produced by the radioactive decay of radium-226, an element found in varying concentrations in many soils and bedrock. Figure 1-1 shows the series of elements that begin with uranium-238 and eventually decay to lead-210. Of all the elements and isotopes in the decay chain, radon is the only gas. Because radon is a gas, it can easily move through small spaces between particles of soil and thus enter a building. Radon can enter a building as a component of the soil gas and reach levels many times higher than outdoor levels.

While many of the isotopes in the uranium-238 decay series exist for a long time before they decay, radon has a half-life of only 3.8 days. Radon decay products have even shorter half-lives than radon and decay within an hour to relatively stable lead-210. At each level of this decay process, energy is released in the form of radiation. This radiation constitutes the health hazard to humans.

When radon and radon decay products are present in the air, some will be inhaled. Because the decay products are not gases, they will stick to lung tissue or larger airborne particles that later lodge in the lungs. The radiation released by the decay of these isotopes can damage lung tissue and can increase one's risk of developing lung cancer. The health risk depends on how long and at what levels a person is exposed to radon decay products. Radon and radon decay products cause thousands of deaths per year in the United States (1).

Like other environmental pollutants, there is some uncertainty about the magnitude of radon health risks. However, we know more about radon risks than the risks from most other cancer-causing substances. This is because estimates of radon risks are based on the studies of cancer in humans (underground miners). Additional studies of more typical populations are underway. Smoking combined with exposure to elevated levels of radon is an especially serious health risk.

Children have been reported to have greater risk than adults of certain types of cancer from radiation, but there are currently no conclusive data on whether children are at greater risk than adults from radon.

Radon levels are usually measured in picocuries per liter of air (pCi/L). Currently, it is recommended that indoor radon levels be reduced to less than 4 pCi/L. But the lower the radon level, the lower the health risk; therefore, radon levels should be reduced to as close to ambient levels as feasible (0.4 pCi/L). For additional information on the estimated health risks from exposure to various levels of radon, refer to EPA's *A Citizen's Guide to Radon, Second Edition* (1).

Architects and engineers should consider the health risks of radon prior to constructing new buildings or renovating existing buildings in radon-prone areas. Including radon pre-

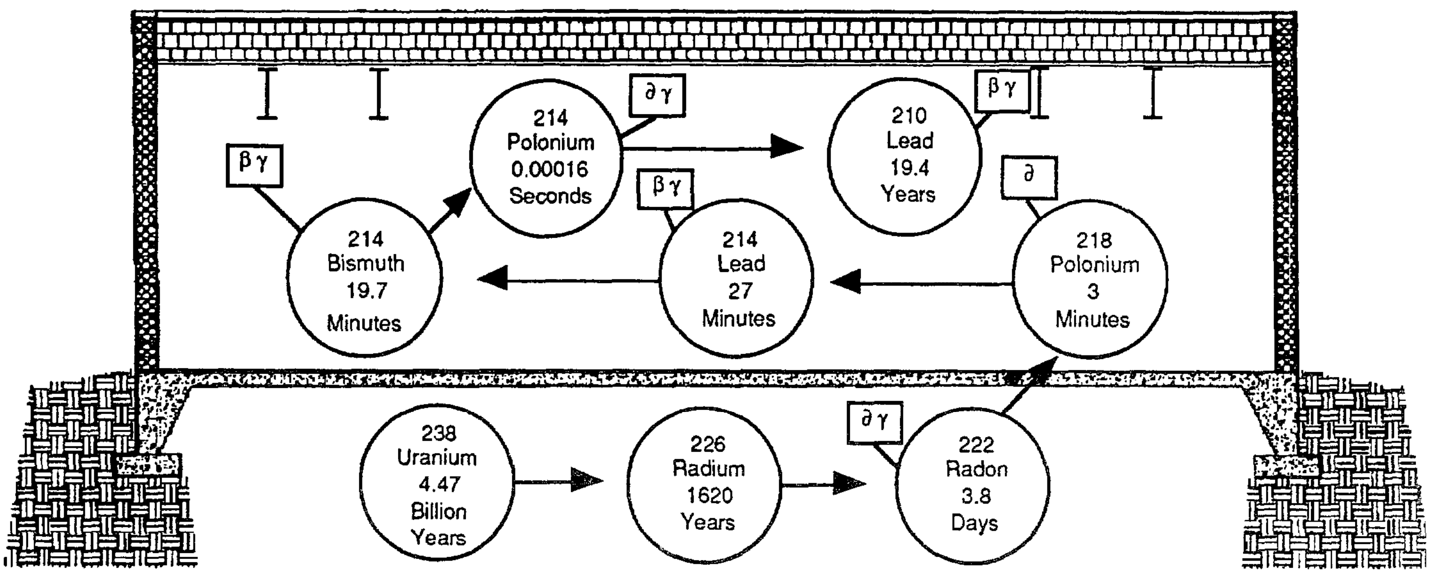

Figure 1-1. **Radon decay chart.** Time shown in half-life.

vention techniques during building design and construction will reduce the chance that a building will have a radon problem and also reduce the cost of reducing radon levels, if needed.

1.3.2 How Radon Enters a Building

The most common way for radon to enter a building is from the soil gas through pressure-driven transport. Radon can also enter a building through diffusion, well water, and construction materials. These modes of radon entry are briefly explained below.

Pressure-Driven Transport

Radon can enter a building through pressure-driven transport only if all of the following four conditions exist:

1) a source of radium to produce radon
2) a pathway from the source to the building
3) an opening in the building to permit radon to enter the building
4) a driving force to move radon from the source into the building through the opening

Pressure-driven transport is the most common way radon enters a building. Pressure-driven transport occurs when a lower indoor air pressure draws air from the soil or bedrock into the building. This transport happens in many schools and other large buildings because these buildings usually operate at an inside air pressure lower than that of the surrounding soil. Negative pressure inside buildings is due in part to building shell effects. For example, indoor/outdoor temperature differences, wind, and air leaks in the shell of the building can contribute to negative pressures in the building. The design and operation of mechanical ventilation systems that depressurize the building can also greatly influence radon entry. Sources of negative pressure in a typical building are shown in Figure 1-2.

Other Ways Radon Enters a Building

Radon also can enter buildings when there are no pressure differences. This type of radon movement is called diffusion-driven transport. Diffusion is the same mechanism that causes a drop of food coloring placed in a glass of water to spread through the entire glass. Diffusion-driven transport is rarely the cause of elevated radon levels in existing buildings. It is also highly unlikely that diffusion contributes significantly to elevated radon levels in schools and other large buildings.

Another way radon can enter a building is through well water. In certain areas of the country, well water that is supplied directly to a building and that is in contact with radium-bearing formations can be a source of radon in a building. At this writing, the only known health risk associated with exposure to radon in water is the airborne radon that is released from the water when it is used. A general rule for houses is that 10,000 pCi/L of radon in water contributes approximately 1 pCi/L to airborne radon levels. It is unlikely that municipal water supplied from a surface reservoir would contain elevated levels of radon and, thus, buildings using this source of water should not need to conduct radon testing of the water.

Radon can also emanate from building materials. However, this has rarely been found to be the cause of elevated levels in existing schools and other large buildings. The extent of the use of radium-contaminated building materials is unknown but is generally believed to be very small.

Because pressure-driven transport is by far the most common way radon enters a building, this manual does not address the other ways that radon can enter a building.

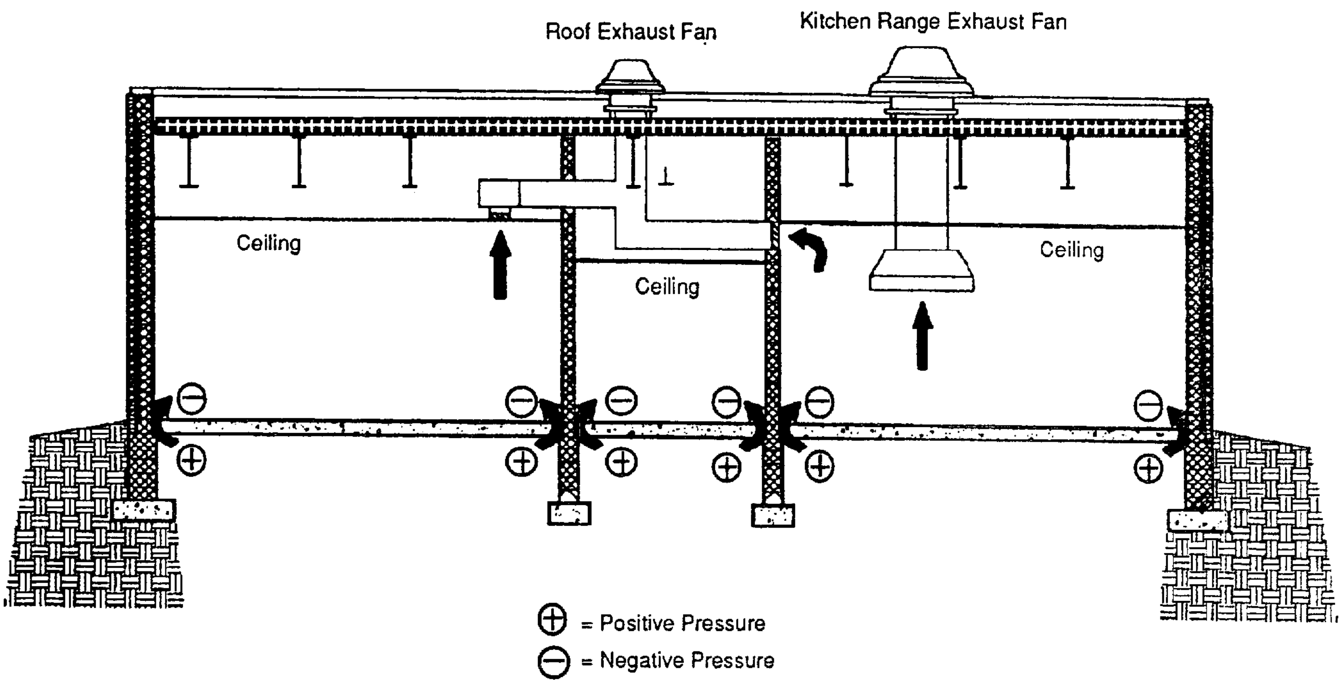

Figure 1-2. Examples of negative pressure sources in a typical building.

Radon Entry and Substructure Type

Elevated levels of radon can occur in any building regardless of foundation type. Figures 1-3, 1-4, and 1-5 show common radon entry routes for buildings constructed on slab-on-grade, basement, and crawl space foundations, respectively. Because a large majority of the new buildings constructed today are slab-on-grade substructures, Section 2.1 of this manual emphasizes radon prevention for slab-on-grade buildings. However, many of the radon prevention techniques used for slab-on-grade substructures are also applicable to basements and crawl spaces.

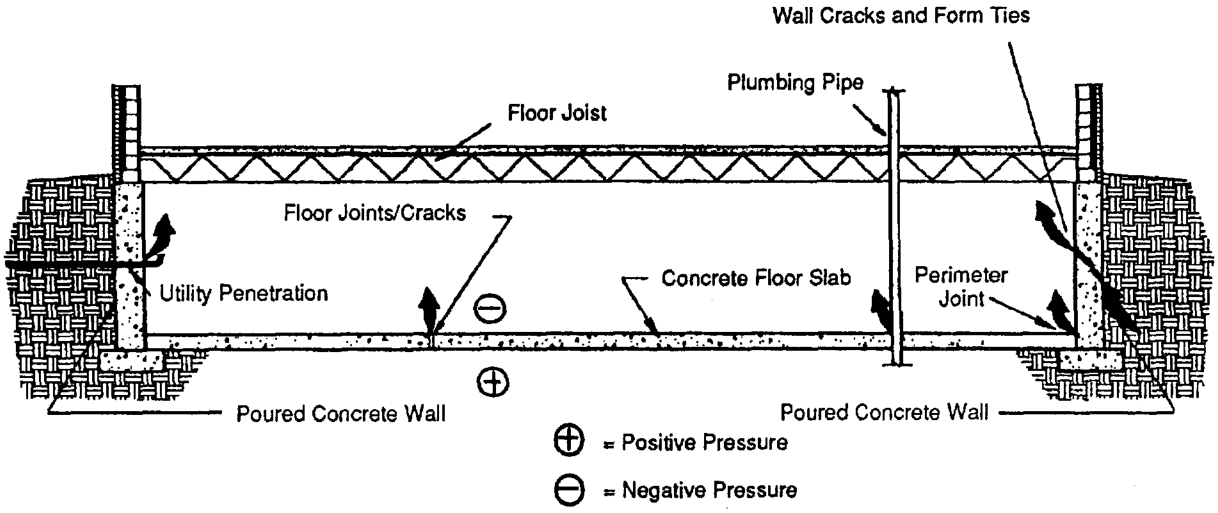

Figure 1-3. Typical radon entry routes in slab-on-grade construction.

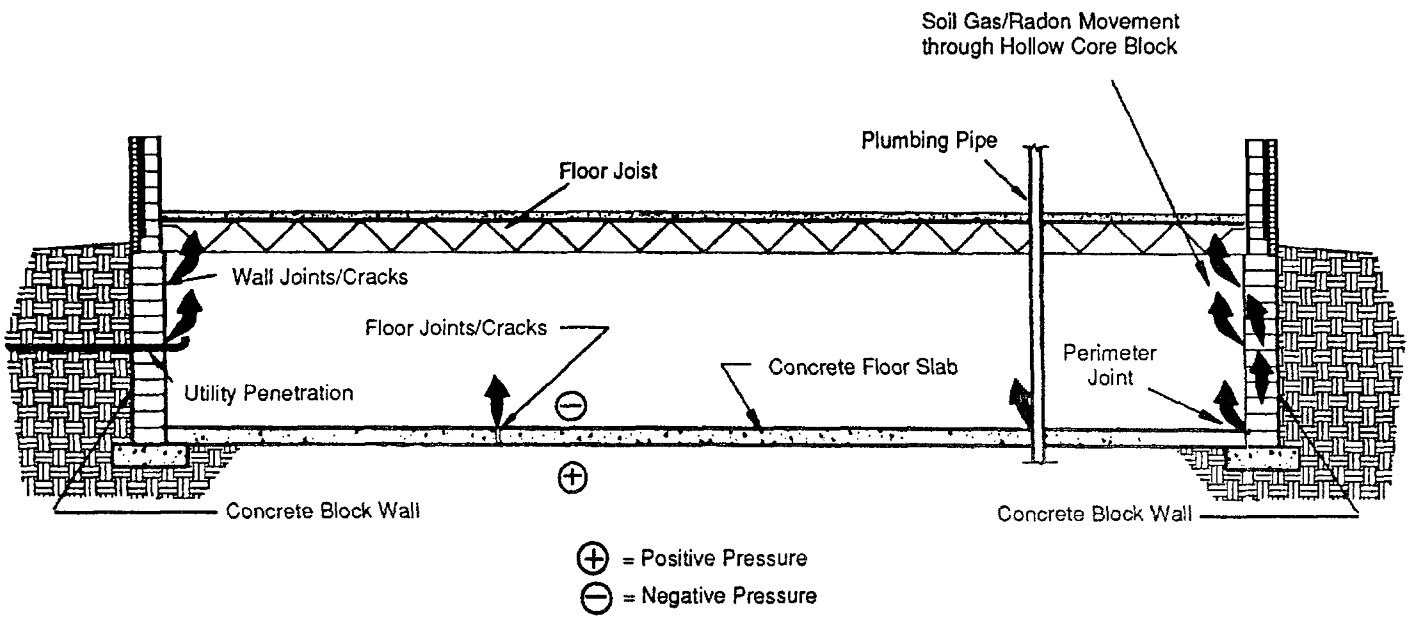

Figure 1-4a. Typical radon entry routes in concrete block basement walls.

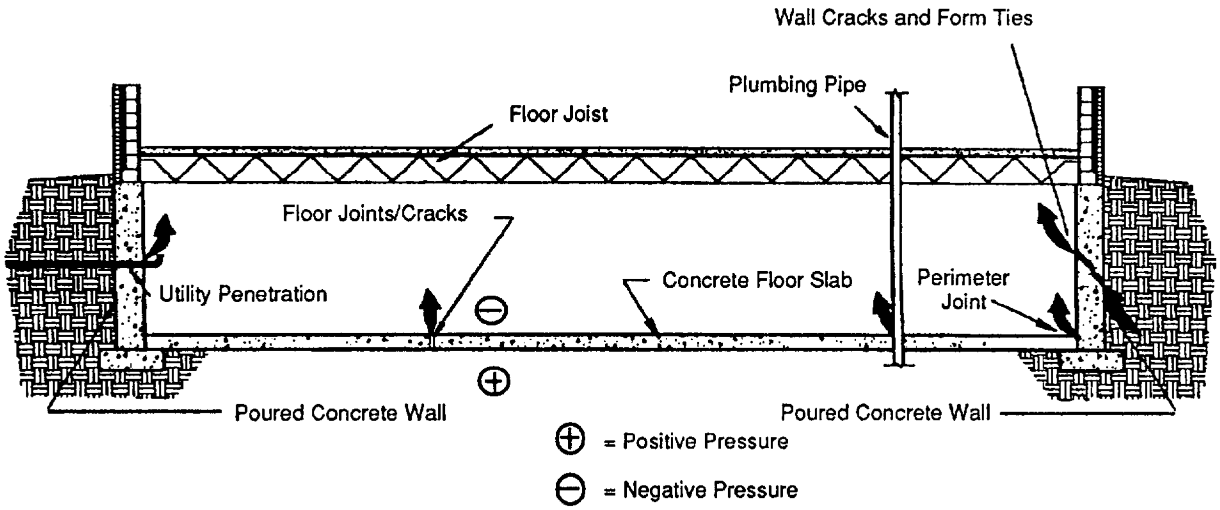

Figure 1-4b. Typical radon entry routes in poured concrete basement walls.

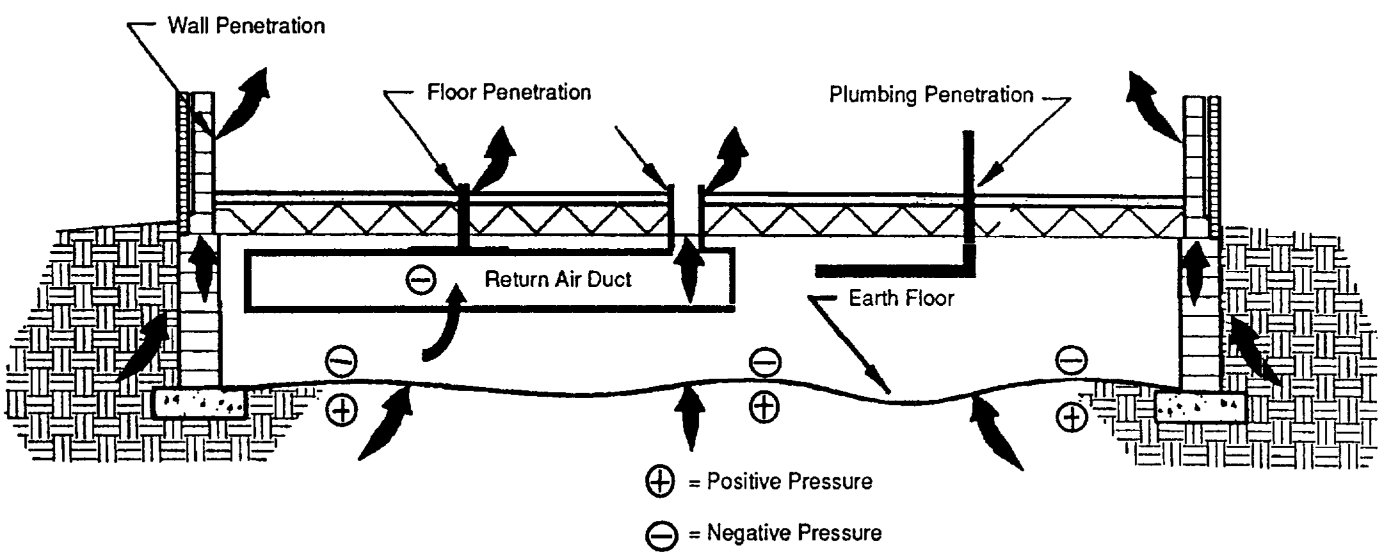

Figure 1-5. Typical crawl space foundation entry routes.

The specific additional requirements for basement substructures (such as sealing of basement walls) are discussed in Section 2.1.3. The additional recommended requirements for crawl spaces are discussed in Section 2.1.4 (submembrane depressurization).

1.3.3 How to Determine if Radon Prevention is Needed

An often-asked question is "Can one determine if radon-resistant construction techniques are necessary for a given site?" A simple and inexpensive standardized test that could conclusively identify problem sites would be very helpful. At present there are no reliable, easily applied, and inexpensive methods for correlating the results of radon evaluation tests of soils at a building site with subsequent indoor radon levels contained in a building built on that site. Bedrock and soils interact in complex ways with dynamic building behavior and environmental factors. There are too many combinations of factors that cause elevated indoor radon concentrations for simple correlations to exist.

In the absence of a simple test to determine when radon prevention techniques are needed, the discussion below covers various sources of information to assist architects and engineers with site assessment.

EPA National Radon Potential Map

One source of guidance is the growing body of radon data available at local, state, and regional levels. With these data, EPA is compiling a National Radon Potential Map. The map integrates five factors to produce estimates of radon potential. These factors are indoor radon screening measurements, geology, soil permeability, aerial radioactivity, and substructure type. All relevant data were collected and carefully evaluated so that the five factors could be quantitatively ranked for their respective "contribution" to the radon potential of a given area. The map assigns every county of the U.S. to one of three radon zones. Zone 1 areas have the highest potential for elevated levels, Zone 2 areas also have potential for elevated indoor radon levels but the occurrence is more variable, and Zone 3 areas have the least potential for elevated levels.

The radon potential estimates assigned on the map are stated in terms of predicted average screening levels. They are not intended to predict annual average measurements, but rather to assess the relative severity of the potential for elevated indoor radon levels. We recommend you use this map when it becomes available to help determine when radon prevention construction techniques might be needed.

Radon Levels in Nearby Buildings

Radon levels in a sample of existing U.S. school buildings were recently surveyed by EPA. Measurements to date indicate that many schools and other large buildings throughout the country have rooms or classrooms with radon levels above 4 pCi/L. Many have been measured at levels in excess of 20 pCi/L. It is expected that the geographic distribution of the radon problem in schools and other large buildings will be similar to that for homes. You can contact regional, state, or local officials for information about radon levels in nearby buildings and use this information, together with the National Radon Potential Map, to help decide if you are in a radon-prone area.

Soil

Several studies have attempted to make simple correlations between radon or radium concentrations in the soil and indoor radon concentrations. No direct correlations have been found.

Building Materials

An extremely small percentage of U.S. buildings with indoor radon concentrations greater than 4 pCi/L can be attributed to building materials. Most of the building material problems have arisen from the use of known radium-rich wastes such as aggregate in block or in fill around and under houses, or in areas of buildings with no ventilation. None of the existing large buildings studied in EPA's Air and Energy Engineering Research Laboratory's research program have had any identifiable problem associated with radon from building materials. However, be aware that building materials are a potential problem. But unless building materials have been identified as radium-rich in that region of the country, the chance of obtaining significant radon levels from building materials is very small.

Summary

Based on current research and the additional cost of radon resistant construction features, the expected impact on the building budget will probably be much less than \$1.00 per ft^2 of earth contact floor area in most parts of the country. In most cases (buildings that are already designed to have subslab aggregate and plastic vapor retarder), sealing major radon entry routes and installing an ASD system will add less than \$0.10 - \$0.20 per ft^2 of earth contact floor area to total costs. Therefore, it is often more cost-effective to build using radon prevention techniques, rather than waiting until the building is completed and then having to add a radon mitigation system.

1.4 Radon Prevention Techniques

Like most other indoor air contaminants, radon can best be controlled by keeping it out of the building in the first place, rather than removing it once it has entered. The following subsections briefly describe the recommended radon prevention techniques discussed in Chapter 2 of this manual:

1.4.1 **Soil Depressurization.** A suction fan is used to produce a low-pressure field under the slab. This low-pressure field prevents radon entry by causing air to flow from the building into the soil.

1.4.2 **Building Pressurization.** Indoor/subslab pressure relationships are controlled to prevent radon entry. More outdoor air is supplied than exhausted so that the building is slightly pressurized compared to both the exterior of the building and the subslab area.

1.4.3 **Sealing Radon Entry Routes.** Seal major radon entry routes to block or minimize radon entry.

These radon prevention techniques are relatively inexpensive and easy to install. We recommend that all three of these techniques be used in new construction to ensure maximum radon control.

1.4.1 Soil Depressurization

The most effective and frequently used radon-reduction technique in existing buildings is active soil depressurization (ASD).

How an ASD System Works

An ASD system creates a low-pressure zone beneath the slab by using a powered fan to create a negative pressure beneath the slab and foundation. This low-pressure field prevents soil gas from entering the building because it reverses the normal direction of airflow where the slab and foundation meet. If the low pressure zone is extended throughout the entire subslab area, air will flow from the building into the soil, effectively sealing slab and foundation cracks and holes (2). For a simplified view of the operating principle of an ASD, refer to Figure 1-6. A similar system without a fan for "activation" is referred to as a "Rough-in" of an ASD system, and is briefly discussed at the end of this section.

The following are essential instructions for the design and construction of a soil depressurization system:

- Place a clean layer of coarse aggregate of narrow particle size distribution (naturally occurring gravel or crushed bedrock) beneath the slab.

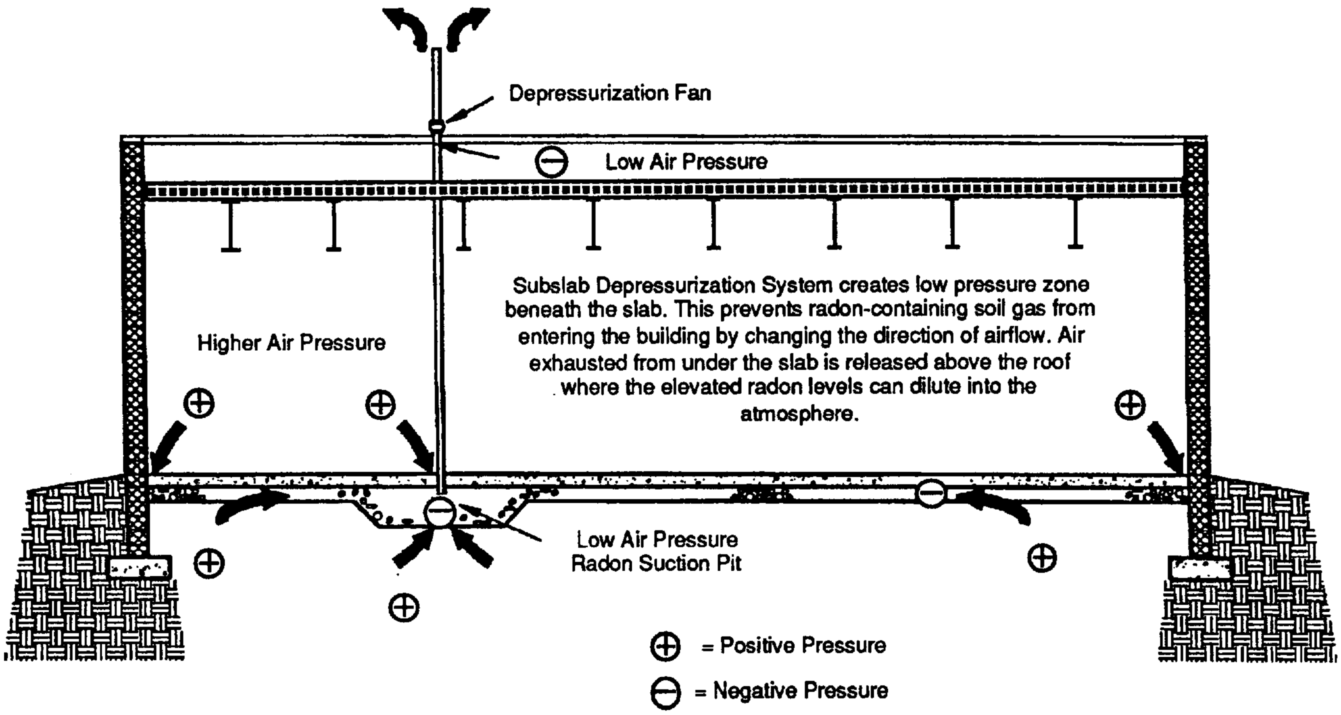

Figure 1-6. Subslab depressurization theory.

- Eliminate all major barriers to extension of the subslab low pressure zone, such as interior subslab walls.
- Install radon suction pit(s) beneath the slab in the aggregate (one radon suction pit for each area separated by subslab walls).
- Install a vent stack from the radon suction pit(s) under the slab to the roof.
- Install a suction fan on the vent stack. (The fan should be operated continuously, and the system should be equipped with a warning device to indicate loss of negative pressure through fan failure or other causes.)
- Seal all major slab and foundation penetrations.

Rough-in for an ASD System

A rough-in for an ASD system is the same as an ASD system except there is no fan. For new construction where radon levels are elevated even marginally, the installation of a rough-in system is a prudent investment and is recommended. If a building is found to have a radon problem, then a rough-in can easily be converted into an ASD system by installing a fan.

Passive Soil Depressurization

Architects and engineers may ask, "Is it possible to install a soil depressurization system that works passively (that is, without a fan)?" Although research has shown that passive systems are sometimes effective in home construction, they are not recommended for use in schools and other large buildings. Many competing negative pressures in large buildings can easily overcome a passive system. Also, the large number of radon suction pits and vent pipes needed for passive systems to be effective in a large building would make installation more expensive than an ASD system. Therefore, in radon-prone areas we recommend you do not use passive soil depressurization systems. We do recommend, as a minimum, that the design features for an ASD system be roughed-in for later activation if needed.

ASD Costs

Several factors affect the cost of an active soil depressurization system. Incremental installation costs for a system designed into a new large building range from as low as \$0.10 per ft^2 of earth contact area to more than \$0.75 per ft^2, depending on the availability of aggregate and sealing costs (3, 4, 5, 6, 7, 8). If aggregate is already part of the design, the costs will be at the low end. Incorporation of the aggregate and vapor retarder is considered good architectural practice and is required by code in most areas of the U.S., and, therefore would not be considered a radon-prevention cost.

For comparison, a recent EPA survey showed that the average cost for installing ASD in an existing school is about \$0.50 per ft^2 (9). These costs could range from about \$0.10 up to \$3.00 per ft^2 of earth contact floor area depending on the structure and subslab materials.

1.4.2 Building Pressurization

Building pressurization involves bringing in more air to the building than is exhausted, causing a slightly positive pressure inside the building relative to the subslab area. The positive pressure in the building causes air to flow from inside the building to the outdoors through openings in the substructure and building shell; this effectively seals radon entry routes. Building pressurization is similar to ASD in that both methods block radon entry routes using air pressure barriers; but the systems are different in that, with building pressurization, air is pushed out of the building from inside rather than being drawn out from under the slab, as in ASD. The following section explains the principles of building pressurization using the heating, ventilating, and air-conditioning (HVAC) systems.

How Buildings Typically Operate

Many buildings (both leaky and tight buildings) tend to maintain an indoor air pressure lower than outdoors. It is often difficult to continuously operate a building to obtain slightly positive pressure conditions unless the building shell is tight and the building HVAC system supplies more outdoor air to each room than is exhausted. This difficulty is due to a complex interaction between the building shell, the mechanical systems, the building occupants, and the climate.

Modern buildings generally are constructed with fan-powered HVAC systems to provide outdoor air to the occupants. Many buildings also have exhaust fans to remove internally generated pollutants from the building. If the systems place the earth contact area under a slightly positive pressure with respect to the subslab, they will prevent radon entry and will dilute radon under the slab for as long as the systems are operating. However, if these fan systems (by design, installation, maintenance, or adjustment) place any earth contact area of the building under a negative pressure with respect to the soil, radon can enter through any openings in the slab.

Important Features of HVAC Systems to Prevent Radon Entry

The following HVAC system features and operating guidelines should be followed for radon prevention:

- In radon-prone areas, eliminate air supply and return ductwork located beneath a slab, in a basement, or in a crawl space in accordance with ASHRAE Standard 62-1989 (10).
- Supply outdoor air in accordance with guidelines in ASHRAE Standard 62-1989 (10).
- Construct a "tight" building shell to facilitate achieving a slightly positive pressure in the building.
- Seal slab, wall, and foundation entry points as noted in Section 1.4.3, especially in areas of the building planned to be under negative pressure by design (such as restrooms, janitor's closets, laboratories, storage closets, gymnasiums, shops, kitchen areas).
- Ensure proper training and retraining of the HVAC system operators, together with an adequate budget, so that the system is properly operated and maintained. (This appears to be a major area of neglect in existing school buildings.)
- In areas with large exhaust fans, supply more outdoor air than air exhausted if possible.

Once radon has entered a building, another way to reduce radon levels is by diluting them with ventilation air (outdoor air). Dilution air should be supplied from outdoors in accordance with ASHRAE Standard 62-1989 (10). To reduce highly elevated radon levels it may be necessary to supply higher quantities of outdoor air than those recommended by ASHRAE. (Note that neither pressurization nor dilution is effective when the HVAC system is not operating, such as in night and week end setback.) Additionally, dilution is not an effective stand-alone radon reduction technique if radon levels are substantially elevated. Dilution is a less reliable and frequently more costly approach than the other radon prevention techniques.

In summary, building pressurization with the HVAC system can reduce radon levels; however, because of the difficulty of properly operating the system in a way that continuously prevents radon entry, building pressurization is not recommended for use as a stand-alone radon-control system in new buildings. When building pressurization is used with the other methods of radon prevention (ASD and sealing of major radon entry routes), building pressurization contributes to low radon levels.

Costs and savings for HVAC systems and a tight building shell are not presented because they are considered good architectural and engineering practice, and moreover, are mandated by many building and energy codes.

1.4.3 Sealing Radon Entry Routes

Because the greatest source of indoor radon is almost always radon-containing soil gas that enters the building through cracks and openings in the slab and substructure, a good place to begin when building a radon-resistant building is to make the slab and substructure as radon-resistant as economically feasible.

However, it is difficult, if not impossible, to seal every crack and penetration. Therefore, sealing radon entry routes and constructing physical barriers as a stand-alone approach for radon control in schools and other large buildings, is not currently recommended. On the other hand, sealing of major radon entry routes will help reduce radon levels and will also greatly increase the effectiveness of other radon prevention techniques. For example, sealing increases the effectiveness of ASD by improving the pressure field extension beneath the slab. Sealing also helps to achieve building pressurization by ensuring that the building is a "tight box" without air leakage. Many of these sealing techniques are standard good construction practices.

Sealing Recommendations

Radon entry routes that should be sealed are:

- Floor/wall crack and other expansion joints. Where code permits, replace expansion joints with pour joints and/or control saw joints because they are more easily and effectively sealed.
- Areas around all piping systems that penetrate the slab or foundation walls below grade (utility trenches, electrical conduits, plumbing penetrations, etc.).
- Masonry basement walls.

Limitations of Sealing

Many construction materials are effective air and water barriers and also retard the transfer of radon-containing soil gas. In practice however, the difficulties that arise when using sealing and physical barrier techniques as the only means of control are virtually insurmountable. Physical barriers have proven to be frequently damaged during installation; moreover, failure to seal a single opening can negate the entire effort, especially when radon concentrations are high. Nevertheless, you should seal major radon entry routes; not only will sealing retard radon transfer but sealing will also increase the effectiveness of ASD and building pressurization.

The cost of sealing major radon entry routes is dependent on the building design and local construction practices. For one example, refer to the case study in Appendix A.

1.5 Why Radon Prevention Should be Considered in Building Design

Most of the radon prevention techniques covered in this manual can be applied to existing buildings, but installation will cost more than if these techniques were installed during initial construction. For example, factors that increase the difficulty and cost to install an ASD system in an existing building include:

- Poor communication below the floor slab (i.e., no aggregate or aggregate with many fines or with wide particle size distribution range).
- Barriers to subslab communication (internal subslab walls).
- Radon entry points at expansion and control joints.
- Ease of running the radon vent pipe and power source through and/or out onto the building's roof.
- Building depressurization caused by the HVAC system (or other fans) exhausting more air than is supplied.

All of the above factors can be controlled in new construction. As further research is conducted, additional information on the radon prevention features, or better guidance on when they are not needed, should become more clear and will be documented in future updates of this manual.

Again, we emphasize that it is important to include radon prevention features during design. Including these features during building construction makes their application *easier and costs much less* than adding them after the building is completed.